

# Systematic Bias in 2MASS Galaxy Photometry

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## ABSTRACT

We report the discovery of a serious bias in galaxy photometry reported in the 2MASS Extended Source Catalog (Jarrett *et al.* 2000). Due to an undetermined flaw in the 2MASS surface photometry routines, isophotal and total magnitudes calculated by their methods underestimate the luminosity of galaxies from 10% to 40%. This is found to be due to incorrectly determined scalelengths and isophotal radii, which are used to define the aperture sizes for Kron and total fluxes. While 2MASS metric aperture luminosities are correct (and, thus, colors based on those apertures), comparison to other filters (e.g. optical) based on total magnitudes will produce erroneous results. We use our own galaxy photometry package (ARCHANGEL) to determine correct total magnitudes and colors using the same 2MASS images, but with a more refined surface brightness reduction scheme. Our resulting colors, and color-magnitude relation, are more in line with model expectations and previous pointed observations.

## 1. Introduction

Surface photometry is an important tool in the understanding of galaxy mass and structure. Galaxy luminosity measures the primary baryonic component, (i.e. stellar mass) and structural information traces the gravitational potential. Galaxy formation scenarios make specific predictions on the light distribution of galaxies, so accurate reduction of a galaxy image into a total magnitude and scalelength are important parameters to understanding the fundamental plane and the star formation history of galaxies.

Obtaining the structural characteristics and the total luminosity of a galaxy requires knowledge of its surface brightness profile to a significant depth. In order to extrapolate a total luminosity, isophotal analysis is required to determine how far one needs to integrate a galaxy's light plus to provide sufficient information to extrapolate the light profile.

During a surface photometry project to explore the structure of galaxies by morphological type (Schombert & Smith 2011), we discovered a significant discrepancy between the structural and luminosity parameters that we determined using raw 2MASS images versus those reported by the 2MASS project in their Extended Source Catalog (Jarrett *et al.* 2000). We use this letter to outline the problem, and the solution, for other researchers.

## 2. Sample

Our original project was to perform surface photometry of large galaxies over a full range of morphological types. This type of analysis was previously attempted by 2MASS (Jarrett *et al.* 2003), but their focus was not on the structural characteristics of galaxies, but rather luminosities and colors. The first stage of our project was to understand the surface photometry of ellipticals, the simplest galaxies for structural studies as they have highly symmetric isophotes and very few complications to their light distributions due to extinction or recent star formation.

Our sample was selected from the Revised Shapley-Ames (RSA) and Uppsala Galaxy Catalogs (UGC) in order to cover a magnitude and angular limited sample with sufficient S/N in the 2MASS image library. Our only other criteria was that the galaxies to be studied be free of nearby companions or bright stars which might disturb the analysis of the isophotes to faint luminosity levels. Our final sample contained 421 galaxies all classed 'E' by both catalogs.

We downloaded the 2MASS  $J$ ,  $H$ ,  $K$  regions of the sky around all the galaxies in the sample from 2MASS's Interactive Image Service. These sky images were flattened and cleaned by the 2MASS project and contained all the information needed to produce calibrated photometry. We analyzed the images using our own galaxy photometry package (ARCHANGEL, Schombert 2007), thus, the only difference in the final results is our analysis methods, not the data themselves.

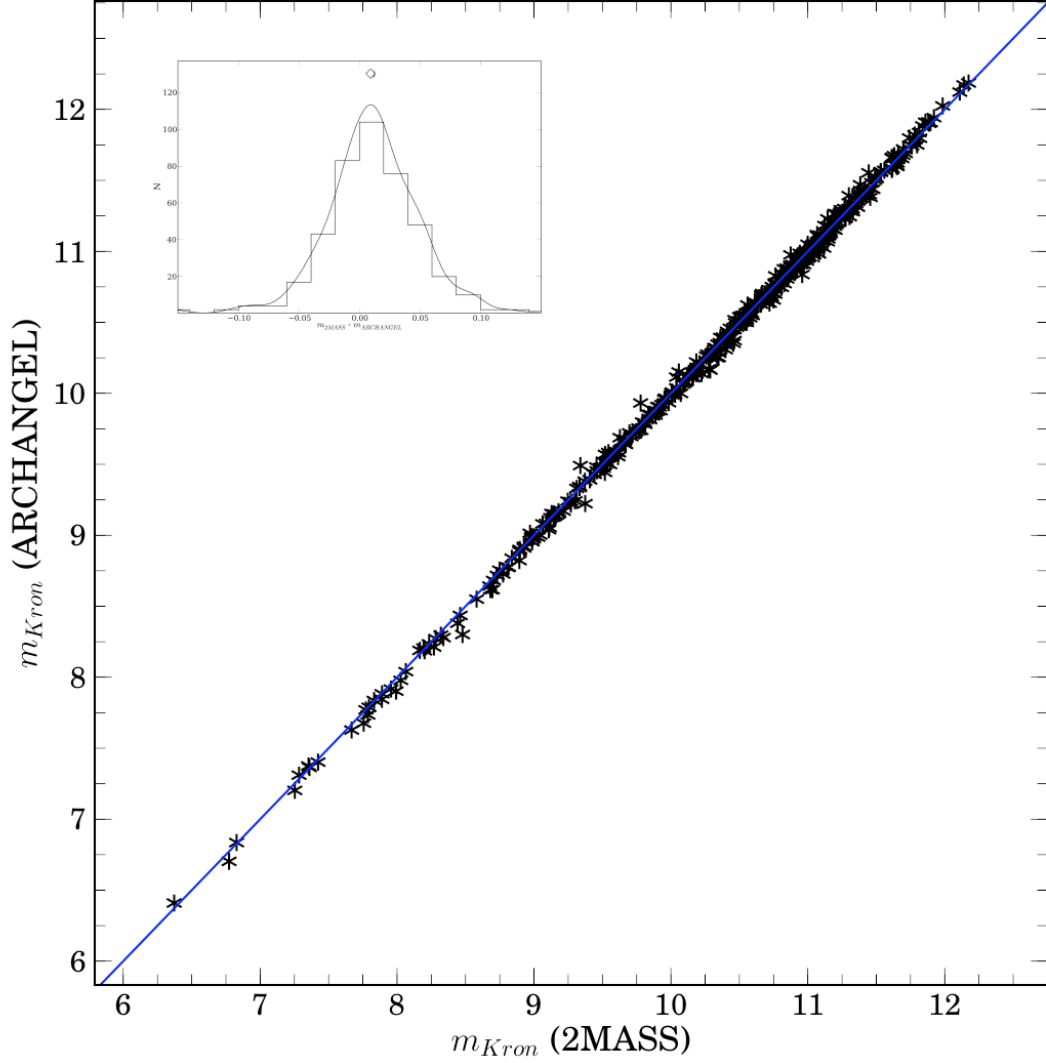
## 3. 2MASS Repeatability

Our obvious first step, once we completed our surface photometry reduction, is to compare our photometric and structural values with those extracted by 2MASS. Metric magnitudes are the simplest for comparison. The 2MASS project provides magnitudes through various aperture sizes (e.g. 14 arcsecs is found in NED) and we were able to reproduce their values in all three bandpasses.

The 2MASS project also provides Kron magnitudes. Kron magnitudes are isophotal magnitudes measuring a galaxy's light through an elliptical aperture whose size is defined by the 20  $K$  mag arcsecs<sup>-2</sup> surface brightness level. These magnitudes contain less intrinsic error as the Kron apertures follow the shape of the galaxy and maximizes the galaxy flux to sky ratio. NED provides those magnitudes and the aperture sizes for all the galaxies in our sample. We compare our Kron magnitudes (using 2MASS's aperture sizes) with their Kron magnitudes in Figure 1.

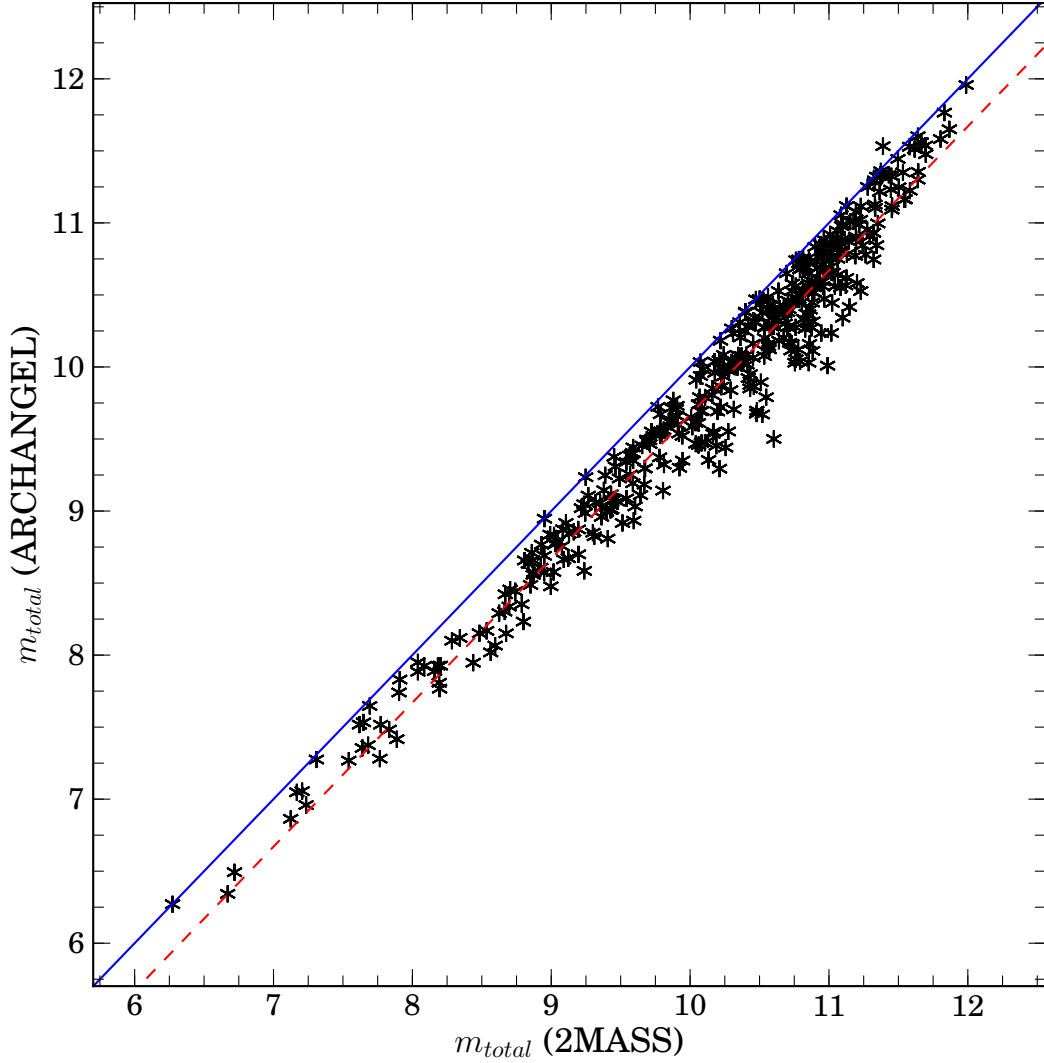
As can be seen from Figure 1, the agreement between our Kron magnitudes and 2MASS values is excellent, meaning that we can reproduce the same fluxes as the 2MASS project using the same apertures. There is a slight offset (0.01 mags) such that our magnitudes are slightly fainter than 2MASS (see inset histogram). This is probably due to the fact that we subtract stars and replace the masked pixels with interpolated galaxy flux which, on average, would lower the aperture flux.

# RSA+UGC ellipticals



**Fig. 1.—** Comparison of 2MASS  $J$  Kron apparent magnitudes for 421 ellipticals on our galaxy structure survey (Schombert & Smith 2011). The blue line is the one-to-one equivalence line. The agreement is excellent as we use the aperture sizes and orientations given by the 2MASS project. The inset histogram is the difference in magnitudes, the mean difference is 0.01 mags (our magnitudes are slightly fainter because of our pipeline reduction procedures that subtract stars and replaces their pixels with interpolated galaxy flux).

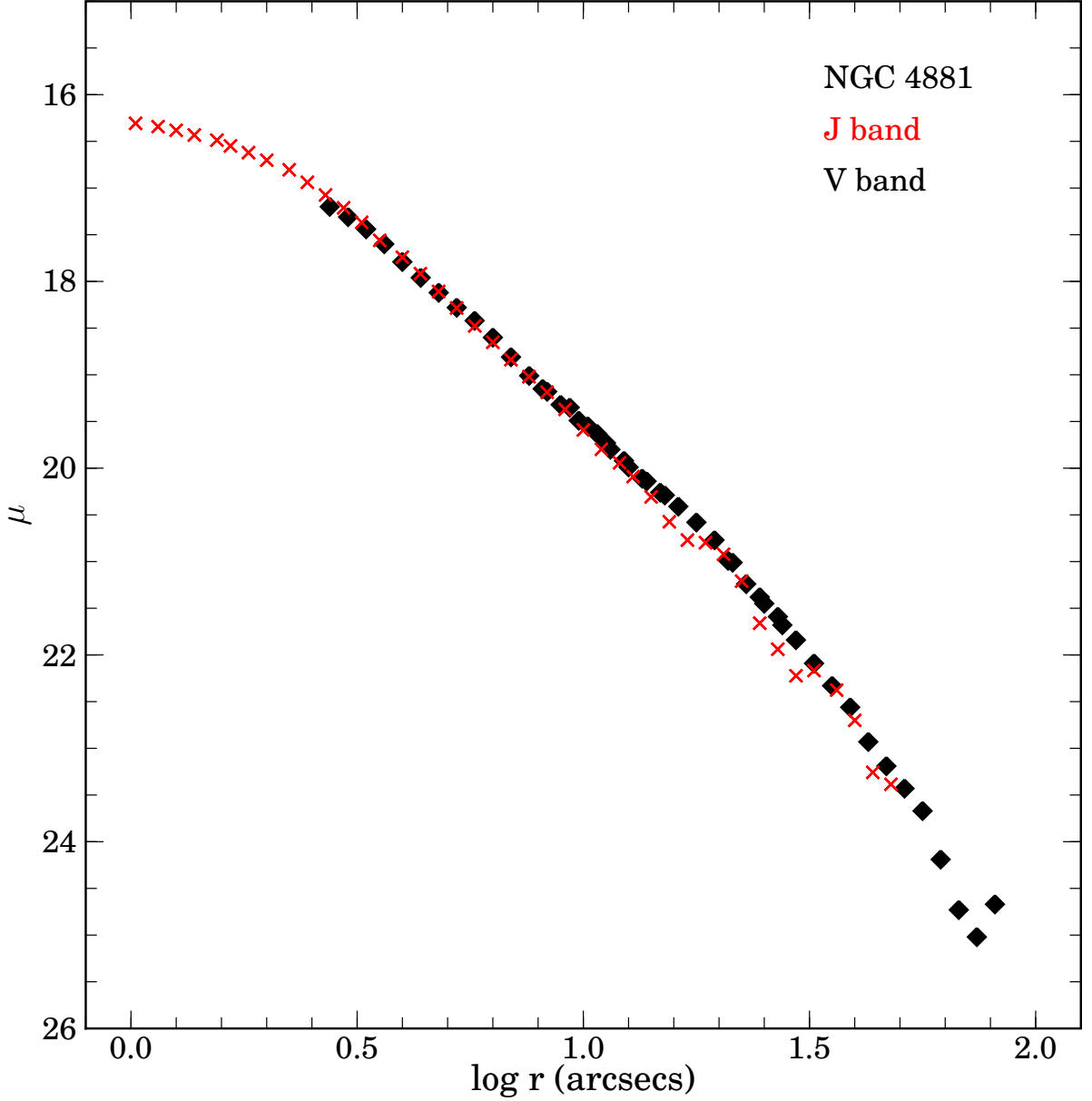
### RSA+UGC ellipticals



**Fig. 2.—** Comparison to total magnitudes ( $J$  band) from the 2MASS Extended Source Catalog with our photometry from the 2MASS raw images. The blue line represents one-to-one correspondence, the red line is a linear fit with a slope of 1.001. The 2MASS total magnitudes are 0.33 mags fainter than our calculated total magnitudes. This represents an error ranging from 10 to 40% in total luminosity.

#### 4. Problems with 2MASS Total Magnitudes

Our next comparison was with our total magnitudes and 2MASS's total magnitudes. That comparison is found in Figure 2 and a significant difference is found between our calculated total



**Fig. 3.—** A comparison of the  $J$  surface brightness profile for NGC 4881 in the Coma cluster and old  $V$  surface brightness data. The  $J$  profile is reduced from 2MASS images using our ARCHANGEL galaxy photometry system. The  $V$  data is from photographic material used in Schombert (1985) shifted for a  $V - J$  color of 2.3. The agreement is excellent considering that the data is separated by 25 years, different wavelengths, different detectors and different reduction software.

This discrepancy in total luminosities is especially puzzling since we can reproduce 2MASS aperture and Kron magnitudes. Thus, we believe the images provided by the 2MASS project are reliable and the calibration is correct. Total magnitudes determined by the 2MASS project use an

aperture magnitude that is four scalelengths in radius where the scalelength is determined Sérsic fits to their surface brightness profiles. Our project determines total magnitudes through asymptotic fits to the curve of growth, where we increase the S/N of the outer isophotes by using the mean intensities give by the surface brightness profiles.

The key difference in our photometric methodology lies in the determination and use of each surface brightness profile. We suspect the difference is because of the methodology used by the 2MASS project, compared to our technique. To explore this hypothesis, we compare the procedures used by 2MASS and ourselves in the next sections in the hope of locating the difference.

#### 4.1. Surface Photometry Comparison

Our procedure for isophotal analysis of galaxies is found in Schombert (2007), and the full data for the galaxies used in this letter will be presented in Schombert & Smith (2011). Our procedure is common to galaxy surface photometry. Ellipses are fit to the isophotes then surface brightness profiles are then constructed from the mean intensities around those ellipses. An example of our final results is shown in Figure 3, a  $J$  profile from 2MASS images and  $V$  profile from old photographic information (Schombert 1985, corrected for a  $V - J$  color of 2.3).

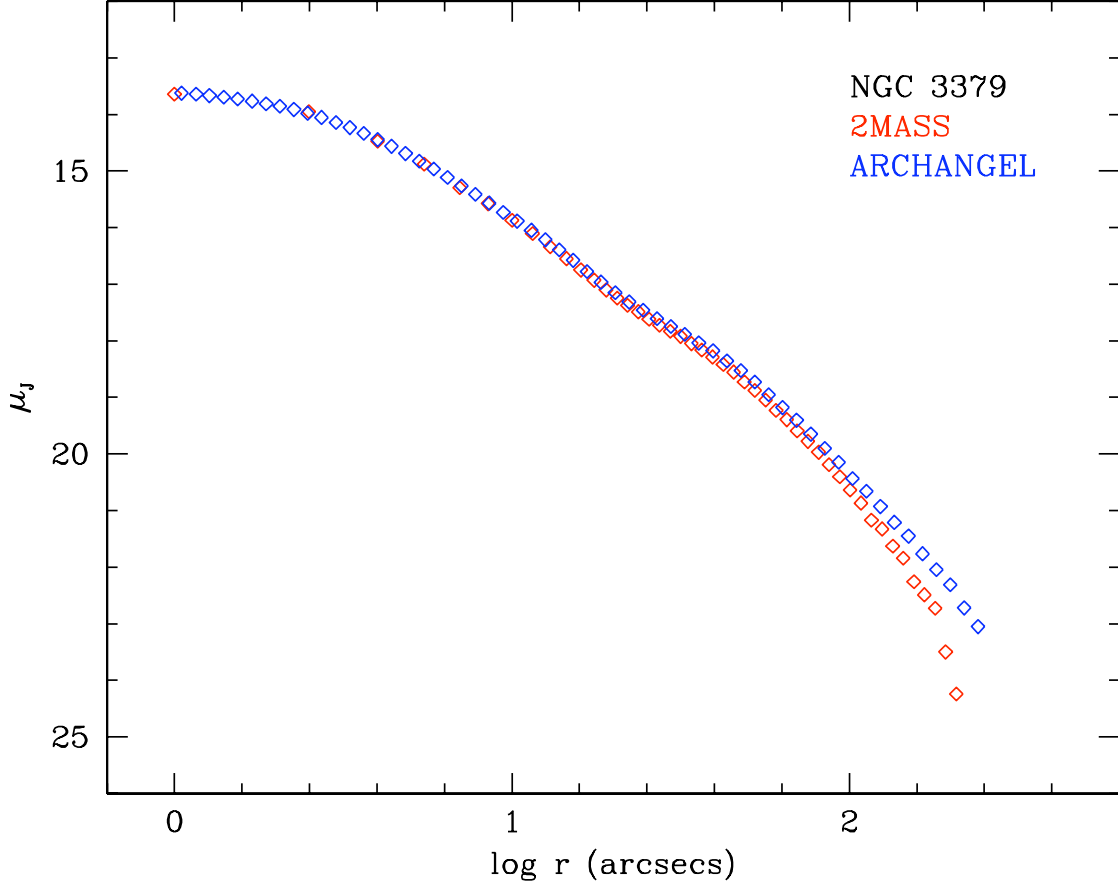
The 2MASS project also published surface brightness profiles for 100 large galaxies (Jarrett *et al.* 2003), 31 of them in common with our elliptical sample. Agreement between our surface brightness profiles and the 2MASS project’s profiles is less than adequate. A comparative example is found in Figure 4, the surface brightness profiles of NGC 3379 from Jarrett *et al.* and our study. The difference between the profiles is extreme at large radii, well beyond expectations from the RMS errors in the data.

The discrepancy for NGC 3379 is not unique. The profile differences for all 31 galaxies is shown in Figure 5, presented as a density distribution of  $\Delta\mu$  versus radius. As can be seen in that Figure, all the comparison galaxies have varying degrees of surface brightness differences, mostly concentrated in the outer regions and can reach 1 to 2 mags arcsecs<sup>-2</sup> in error.

#### 4.2. Data Reduction Differences

One obvious conclusion is that some difference exists in the reduction process that reflects in the final profiles, the data frames themselves are not in question since we can reproduce 2MASS’s aperture luminosities. There are several procedural differences between the isophotal techniques used by the 2MASS project and our photometry package (ARCHANGEL).

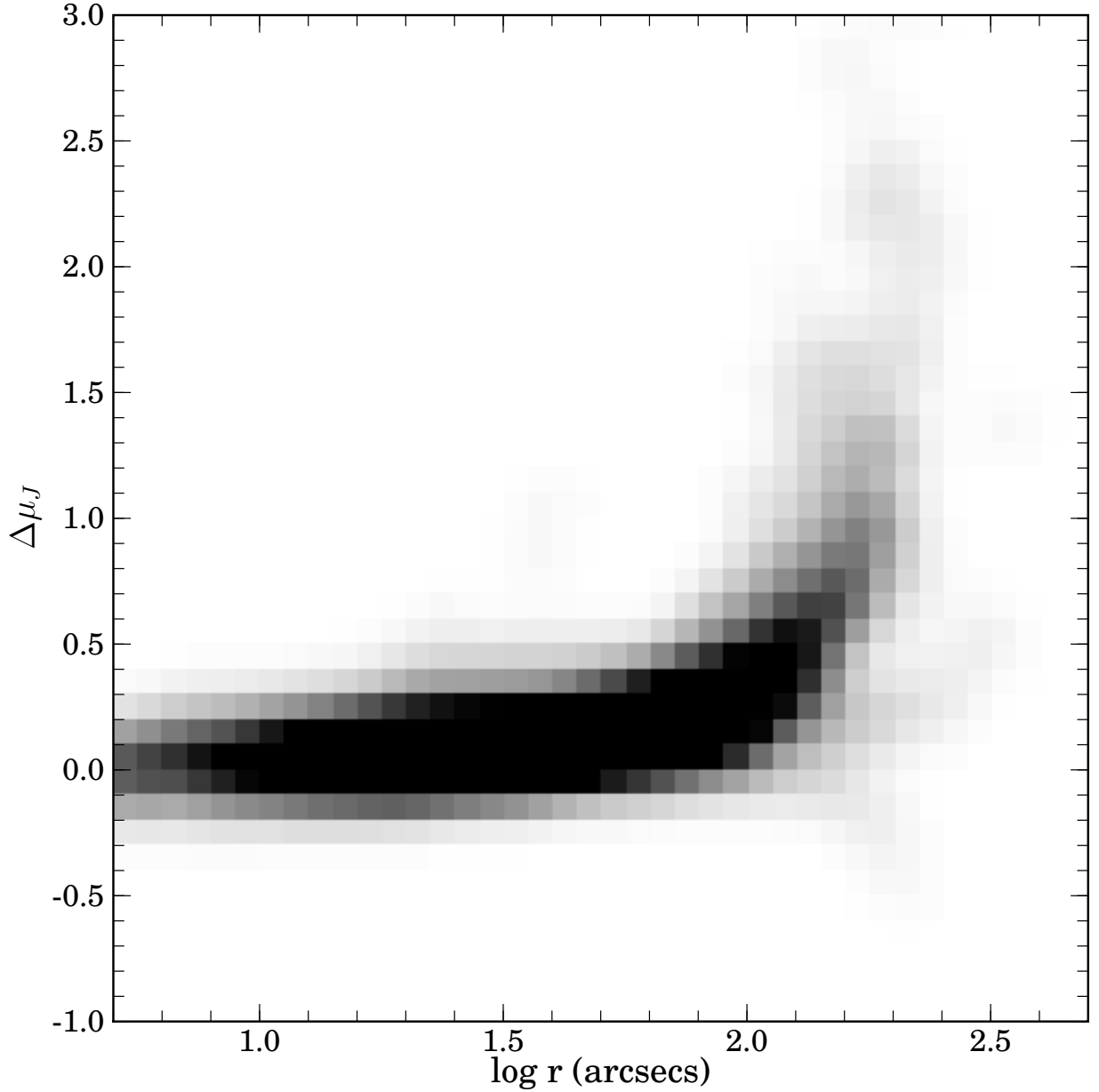
First, the 2MASS project determines an elliptical shape based on a first moment analysis of some intermediate, but high S/N region in a galaxy’s envelope. The calculated eccentricity and position angle are used for the entire galaxy, determining isophote intensity levels based on pixels



**Fig. 4.—** A comparison of the  $J$  surface brightness profile presented by the 2MASS project (Jarrett *et al.* 2003) and the profile reduced by our software package (ARCHANGEL). The photometry agrees at high surface brightnesses, but begins to disagree below 18  $J$  mag arcsecs $^{-2}$ . As discussed in the text, the difference can not be explained by poor ellipse fitting, calibration error or an improper sky value.

around those ellipses. Our project, on the other hand, fits each radii for eccentricity and position angle (as well as x and y center) allowing these ellipse parameters to vary with radius.

This difference in ellipse shape was noted in Schombert (2007), but these difference ellipses are not enough explain the large surface brightness differences found in the galaxy sample (numerical experiments with ellipses in 2MASS data displays only a 1 to 2% difference in intensities). There are a few extreme cases (e.g. LSB galaxy, NGC 3109), but in general ellipticals have fairly constant eccentricities. However, there are large differences in the quoted intensity values per radius between the 2MASS project and our study. These differences range from small to up to 60%, greatest at the lowest intensity values.

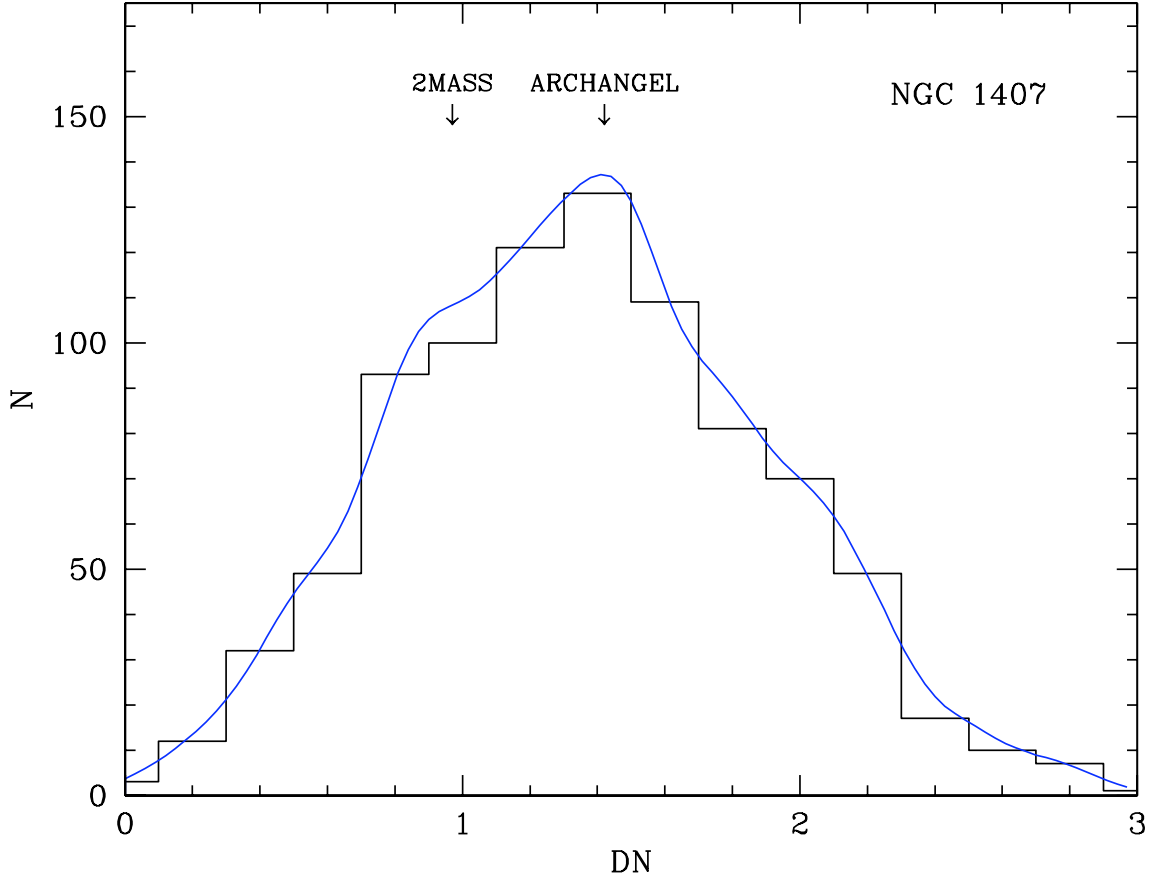


**Fig. 5.—** A density plot of the surface brightness profile differences between the 2MASS project and our study for 421 elliptical galaxies. The differences are primarily found in the outer regions, increasing with galaxy radius. The differences are uncorrelated with the luminosity of the galaxy, size or any other physical characteristic that we can determine.

#### 4.3. NGC 1407: Test Particle

To resolve the differences in the surface brightness profiles, we selected the elliptical NGC 1407 for detailed inspection. NGC 1407 is an excellent test particle for its isophotes are nearly circular (axial ratio of 0.93 from 2MASS, 0.95 from our study) and its envelope is free of any foreground stars or distortions.

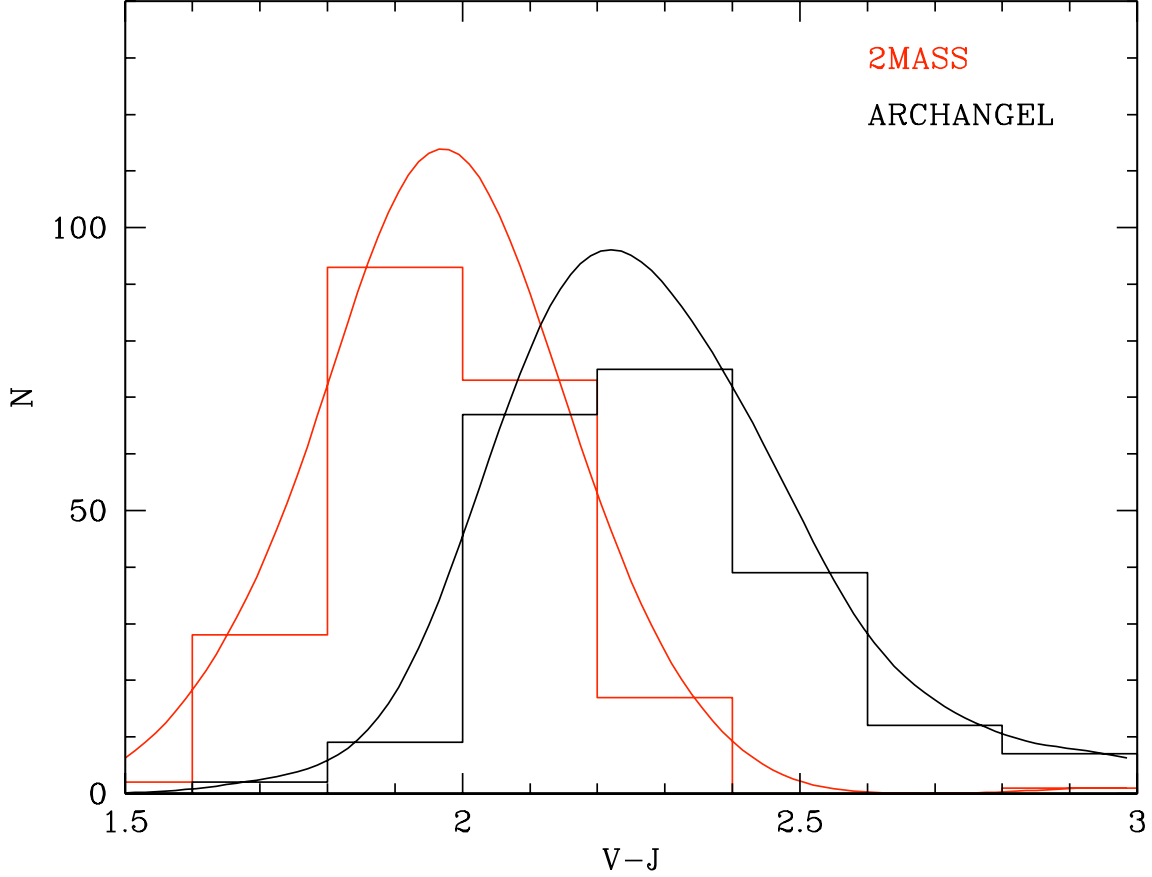




**Fig. 6.—** A histogram of intensity values (in raw data units) for an annulus of 100 arcsecs (width of one pixel) for NGC 1407. The 2MASS project cites a value of 0.97 for this annulus, our study finds an intensity of 1.42. The data clearly supports our higher value. This type of test was completed for all 31 galaxies in our surface brightness overlap sample, all produced the same result.

At 100 arcsecs from the center of NGC 1407, the 2MASS project quotes an isophotal intensity of 0.97 DN ( $20.82 J \text{ mag arcsecs}^{-2}$ ). Our project finds a value of 1.42 DN ( $20.41 J \text{ mag arcsecs}^{-2}$ ). To determine which value more closely represents the isophote at that radius, we have plotted a histogram of intensity values for all pixels between 99.5 and 100.5 arcsecs from the galaxy center. This histogram is shown in Figure 6 (both regular and normalized).

From this Figure, it is obvious that the intensity values deduced by the 2MASS project are not in agreement with the mean value of the pixels in the image, whereas our calculated intensity value is in good agreement with the mean and median value. Since NGC 1407 is a nearly perfect circle in axial ratio, this is not an effect of the ellipse fitting procedure. This is also not due to calibration errors (these are raw data numbers) nor an improper sky subtraction (the differences

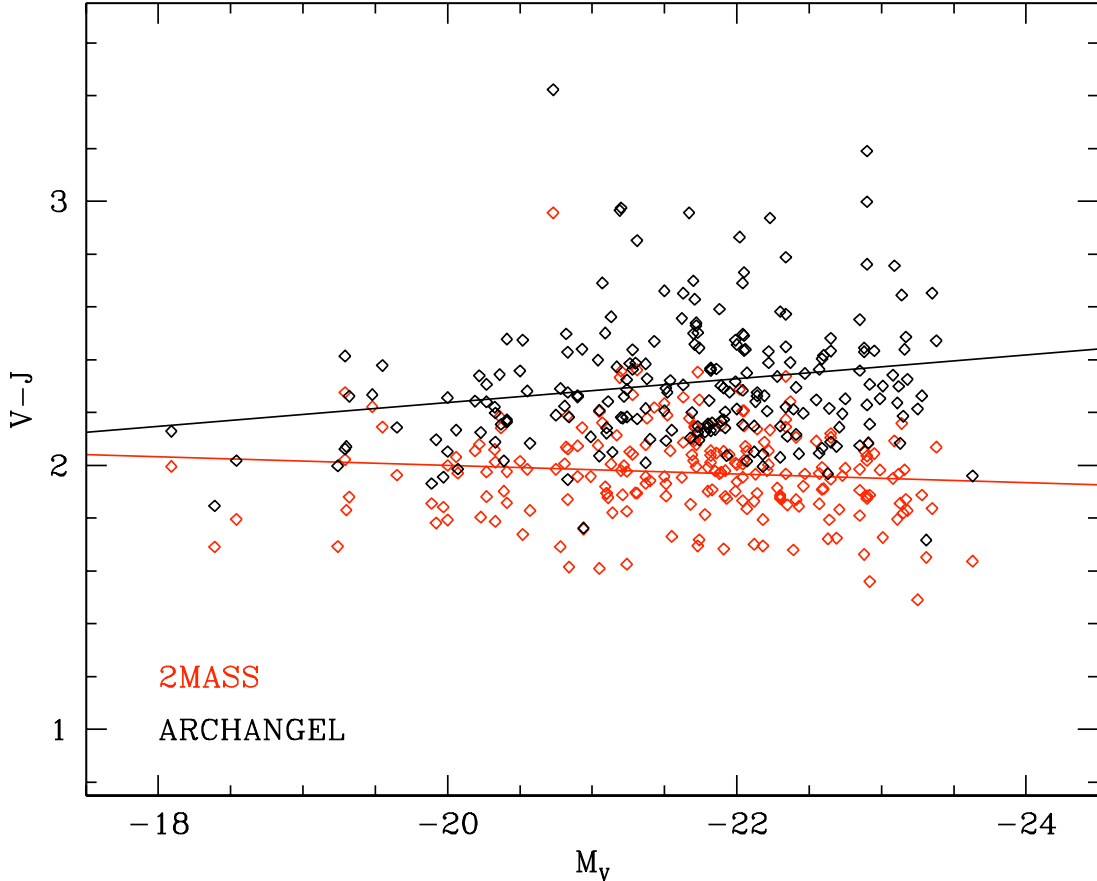


**Fig. 7.—** A histogram of  $V - J$  colors using galactic extinction corrected total magnitudes from 2MASS (extracted from NED) and our study. Since the 2MASS project underestimates the total magnitudes, this reflects into bluer  $V_J$  compared to our colors. SED models predict a  $V - J$  color of 2.5 for a solar metallicity stellar population with an age of 13 Gyrs, in-line with our colors.

would be constant with radius, they are not). We are at a loss to explain 2MASS’s values, however, our values agree with the images (Figure 6) and with past photometry (Figure 3).

The effect these underestimated surface brightness values have on 2MASS photometry is subtle. Both 2MASS Kron and total magnitudes use the surface brightness profiles to deduce isophotal levels (Kron) and scalelengths (total). For Kron magnitudes, the  $20\ K\ \text{mag arcsec}^{-2}$  level is used to define an elliptical aperture. However, since the 2MASS surface brightness profiles underestimate the intensity values per radius, this, in turn, leads to smaller estimates of the isophotal size of the aperture and, therefore, fainter magnitudes.

Total magnitudes for 2MASS are calculated using an outer aperture set to be four times the



**Fig. 8.—** The  $V - J$  color-magnitude diagram for 2MASS colors (red symbols) versus our study (black symbols). Linear fits are shown. The 2MASS project predicts a positive CMR slope, in contradiction with known negative slopes in the literature. Our study finds a negative slope (redder colors with higher galaxy mass, i.e., higher mean metallicity).

scalelength determined by Sérsic function fits. Decreased intensities in the outer regions produce smaller scalelengths, on average, which produce smaller apertures and fainter total magnitudes. This is exactly what we observe in Figure 2.

## 5. Summary

First, we note that this discrepancy has no impact on projects which use 2MASS aperture colors. For galaxy colors are calculated using 2MASS total magnitudes still use the same sized apertures for  $J$ .,  $H$  and  $K$ , and the colors will remain consistent (although for a smaller portion of the total galaxy light). However, comparison between other total magnitudes (e.g. RC3

magnitudes) and 2MASS Kron or total magnitudes will be biased towards the blue.

An example of this is shown in Figure 7, a histogram of  $V - J$  colors for the 421 ellipticals in our sample. As can be seen, the 2MASS colors are 0.25 mags bluer than colors calculated from our total magnitudes since the RC3  $V$  magnitude is determined from an asymptotic fit and, therefore, contains more flux than 2MASS’s total magnitude. There appears to be no standard correction from 2MASS colors to the correct colors, this would require information on how deviant the 2MASS surface brightness profiles (from which the aperture sizes are extracted) are from reality. There appears to be no simple formula.

A priority science goal for 2MASS was large baseline color comparison. An example of relevance of large wavelength comparisons is the color-magnitude relation (CMR). The CMR is a long known correlation between galaxy color and luminosity. The best explanation is that galaxies with higher mass have higher metallicities. Global metallicity reflects in the mean temperature of the RGB such that low metallicities produce bluer colors. The CMR for this data sample is shown in Figure 8. Again, we see that the 2MASS colors predict the *opposite* expectation from earlier optical work in that they find roughly bluer colors with higher luminosity. Using our total magnitudes (combined with RC3 colors) restores the correct CMR, redder colors with higher galaxy luminosity.

We summarize our findings as the following:

- (1) 2MASS aperture magnitudes are reproducible with high accuracy when the same metric apertures are used regardless of shape.
- (2) Comparison between our photometry packages total or Kron magnitudes and 2MASS’s values (from the Extended Source Catalog, Jarrett *et al.* 2000) find serious bias in the 2MASS luminosities of between 10 to 40%.
- (3) Point by point comparison of the surface brightness profiles provided by Jarrett *et al.* (2003) indicate that problem lies in the intensity values deduced by each photometry pipeline. 2MASS values are increasingly fainter with increasing radius, this results in surface brightness profiles that are smaller in isophotal radius compared to our profiles.
- (4) Comparison to raw intensity values (e.g., the 100 arcsecs annulus in NGC 1407) demonstrates that, for unknown reasons, the 2MASS project extracts lower intensity values than given by the images. This is either a flaw in the processing pipeline or an error in the data storage system.
- (5) Underestimated intensity values produces smaller isophotal radii at constant surface brightness and smaller scalelength fits. Both result in smaller apertures and underestimated luminosities.
- (6) While logically, either our photometry or 2MASS’s is in error, we consider three pieces of evidence to indicate our values are correct. First, the direct comparison of intensity values from the raw images. Second, the final  $V - J$  colors where our colors are in agreement with

mean elliptical colors in the literature, the 2MASS project’s values are 0.25 too blue. Third, there is a negative slope in the CMR from 2MASS data, ours data correct matches the color slope expected from SED models and optical CMR’s.

It is highly confusing on why this discrepancy has not been noticed to date. Either we have become too trusting of electronically available datasets. Or we simply, due to pressures to publish, are not as thorough in our data analysis, especially with respect to external checks. We becoming increasingly vulnerable to systematic errors with increasing automation to our datasets, leading to potentially highly embarrassing errors in our science results.

Acknowledgements: Most of the comparative values were extracted from NED (NASA’s Extragalactic Database) using new network tools. The quick access to difference galaxy catalogs on one site made this project doable in reasonable timescales. The model for future science is not faster cycles, but faster and clearer access. The software for this project was supported by NASA’s AISR and ADP programs.

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